Fabrication control of the resonance frequencies of high-index-contrast microphotonic cavities

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Abstract: Microphotonic filters require precise control of the relative resonance frequencies of integrated dielectric micro-cavities. Using high-index-contrast microring resonators, we present, demonstrate, and analyze techniques allowing small and accurate corrections of resonance frequencies at fabrication.

OCIS codes: (230.3120) Integrated optics devices; (230.4000) Microstructure fabrication; (230.5750) Resonators

1. Introduction

High-index-contrast (HIC) resonators show unique characteristics such as large free spectral range (FSR) and widely tunable resonances. To create integrated filters, these resonators must be coupled together and to access ports. As shown in [1], the dielectric perturbation due to a coupling region shifts the resonance frequency of a resonator. This is referred to as coupling induced frequency shift (CIFS). In addition, fabrication related imperfections, such as lithographic proximity effects, create a frequency shift of their own. Both of these frequency shifts scale with the coupling strength. Hence, a frequency mismatch will appear between two presumably identical resonators that are coupled to their environment with different strengths. In coupled-resonator microphotonic filters, the resulting frequency mismatch can be of the order of the filter bandwidth and significantly alter the spectral response [2-3].

In principle, all repeatable resonance frequency deviations can be corrected at fabrication. However, the correction required to compensate for frequency shifts in high-index-contrast filters cannot be accurately introduced by simply changing the dimensions of a resonator in the lithographic layout used at fabrication. This is because the required dimensional changes are often below the minimal spatial discretization of the maskless lithography tools used to create the shape of the resonator on a lithographic mask or directly on a wafer. Hence, techniques allowing small and accurate corrections of resonance frequency at fabrication are needed for acceptable operation of high-order filters based on high-index-contrast resonators. In addition, such techniques are needed in wavelength division multiplexing to accurately spectrally space microphotonic filters that operate on distinct spectral channels.

In this paper, we present, demonstrate, and analyze techniques allowing small and accurate resonance frequency alteration at fabrication. The expected frequency corrections are calculated and compared to experiment. Third-order series-coupled microring filters are used throughout the paper to illustrate the problems. Silicon-rich silicon nitride (SiN) microrings were used in the experiments.

2. Two approaches to frequency correction at fabrication

The two main approaches to frequency correction are shown in Fig. 1. Third-order microring filters are used for illustration purposes but the techniques are applicable to all microphotonic resonators. If a maskless lithography technique such as scanning-electron-beam lithography (SEBL) is used, a small and accurate dimensional alteration can be introduced by changing the exposure dose of a given resonator. In Fig. 1(a), increasing the exposure dose of

Fig. 1 Two approaches to frequency trimming at fabrication. (a) When a maskless lithography technique is used such as scanning-electron-beam lithography, the exposure dose of a given resonator can be altered to introduce slight dimensional changes resulting in precise resonant frequency trimming. (b) When a mask-based lithography is employed such as optical projection lithography or nano-imprint lithography, a non-resonant dielectric structure evanescently coupled to the resonant mode is introduced to precisely modify the resonant frequency of the micro-cavity.

the middle microring will slightly increase its ring-waveguide width and lower its resonance frequency. If a replication lithography technique is used such as optical projection lithography or nanoimprint lithography, the correction technique of Fig. 1(a) can still be used if applied at mask writing. Otherwise, a non-resonant secondary dielectric structure can be formed in proximity to the resonator as shown in Fig. 1(b). It will alter the resonance frequency through interaction with the evanescent tail of the resonant mode. In addition, if both the resonator and the secondary dielectric structure are on the same lithographic layer, the lithographic proximity effects emerging from the interaction of the two patterns will lower the frequency of the resonator by increasing the primary-ring-waveguide width.

We have previously used the technique of Fig. 1(a) to fabricate high-order filters based on frequency-matched microring resonators [3-4]. Below, a detailed analysis of the resonance-frequency control provided by this technique is presented.

3. Calculated resonance frequency corrections

The resonance frequency correction due to an alteration of the exposure dose can be obtained by first computing the dimensional change introduced by the dose alteration and, then, the corresponding resonance frequency correction. In this work, we present calculation results performed for SiN microrings fabricated with a Raith 150 SEBL. The e-beam proximity function was first experimentally determined for the dielectric multilayer used at fabrication. The e-beam proximity function describes the spatial distribution of the resist exposure around the center of the e-beam. Its shape results from the interaction of the e-beam with matter. Once the proximity function is known, the dose profile can be obtained by convolving the proximity function with the pattern scanned by the e-beam. When a high contrast e-beam resist is used, the resist pattern can be assumed to follow, in the dose profile calculated, the contour of constant dose corresponding to the resist's threshold. The shape of the resonators and all relative dimensions will follow approximately the resist pattern but the absolute dimensions of the resonators may be consistently offset from it by the fabrication process. The computation is presented in greater detail in [5].

Calculated resonance frequency corrections for the middle microring of a third-order series-coupled microring filter, designed for a flat-top drop-port response and a 40 GHz bandwidth, are presented in Fig. 2(a). The primary dose, the uniform dose used on all microrings when no correction is applied, impacts the frequency correction obtained with a given dose increase. The primary dose is expressed here with respect to the minimum proximity effects (MPE) dose, the uniform dose minimizing the width variations due to lithographic proximity effects in the filter. The dimensional variations due to lithographic proximity effects will create a frequency mismatch between the outer resonators and the middle resonator of a third-order filter. This frequency mismatch needs to be corrected for appropriate filter operation and is shown in Fig. 2(b) as a function of the primary dose. Interestingly, the primary dose has a significant effect on the relative resonance frequencies. Assuming that the ratio of the primary dose to the resist threshold can be controlled to 2% while the dose increase can be controlled to 0.05%, the relative frequencies

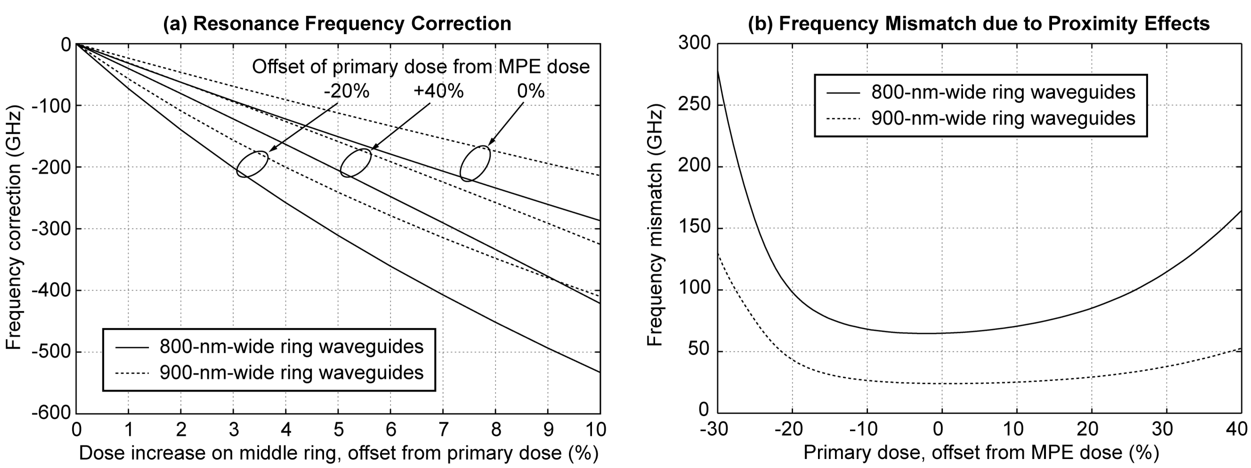

Fig. 2 (a) Calculated resonance frequency corrections for the middle microring of a third-order series-coupled microring filter for various e-beam dose increases. The microrings have an outer radius of 8 μm. The ring waveguides are formed of 400-nm-high SiN (n=2.18) core, 3-μm-high SiO_2 (1.45) undercladding, and air overcladding. 800- and 900-nm-wide ring waveguides are investigated. (b) Frequency mismatch due to lithographic proximity effects between the outer microrings and the middle microring. The global e-beam dose is expressed with respect to the minimum proximity effects (MPE) dose, the global dose minimizing the width variations due to lithographic proximity effects in the microring filter.

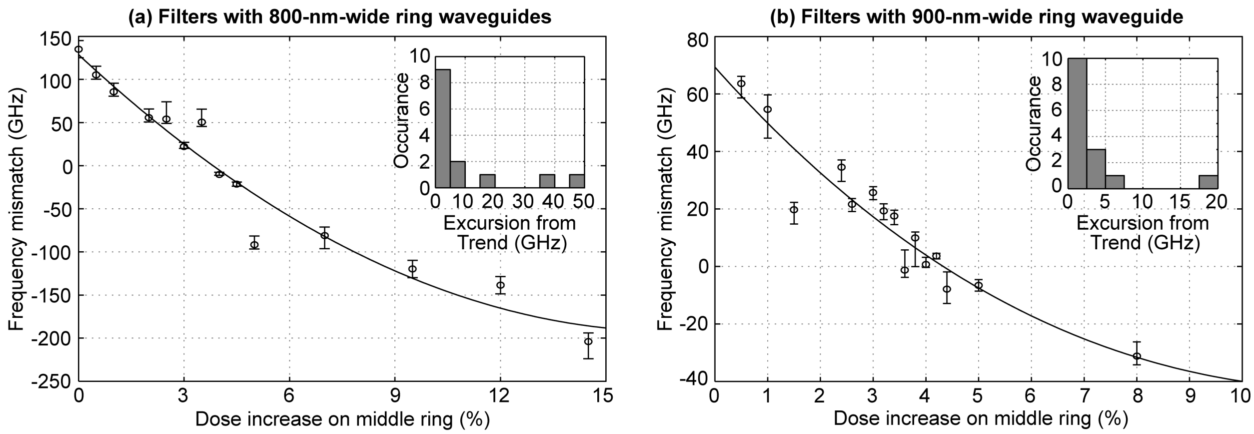

Fig. 3 Experimentally obtained resonance frequency corrections in SiN microrings with (a) 800- and (b) 900-nm-wide ring waveguides. The correction was applied on the middle microring of a third-order microring filter. The frequency mismatch between the outer microrings and the middle microring was measured via fitting the filter spectral response to an analytic model. The insets show the frequency excursions that cannot be explained by measurement and fitting errors. The initial frequency mismatch observed with 0% dose increase is attributed to coupling-induced frequency shift (CIFS) and lithographic imperfections such as proximity effects.

can potentially be controlled to 1-2 GHz in the SiN microrings. This corresponds to better than 50 pm control of the average ring-waveguide width of a microring.

4. Experimentally obtained resonance frequency corrections

The microring filters described in Sec. 3 were fabricated with various dose increases on the middle ring. The SiO_2 undercladding was created via thermal oxidation of the Si wafer, the SiN core was deposited by low-pressure chemical vapor deposition, and the patterns were written using a Raith 150 SEBL and transferred to the SiN using reactive-ion etching [5]. The frequency mismatch between the outer microrings and the middle ring was measured via fitting the spectral response of a filter to an analytic model. Results are presented in Fig. 3. The insets show the frequency mismatch excursions that cannot be explained by measurement and fitting errors. The fabrication process was thoroughly re-optimized after fabrication of filters with 800-nm-wide ring waveguides and before fabrication of filters with 900-nm-wide ring waveguides [5]. A clear improvement in stochastic variations is observed. Nonetheless, the deviations remain significant and illustrate the importance of minimizing, in design, the frequency sensitivity to resonator shape. In the present case, the 900-nm-wide ring waveguides show reduced resonance frequency sensitivity to ring-waveguide width variations when compared to the 800-nm-wide ring waveguides. The resonance shift for a change of 1 nm in average ring-waveguide width is 30 and 42 GHz, respectively.

For small dose increases, the calculated and the observed frequency corrections match well. For large dose increases, a leveling is observed in the empirical curves but not in the calculated ones. This leveling is difficult to explain by lithographic effects and is probably due to the impact of the remaining fabrication steps. Hence, the calculation provides a valuable estimate but an empirical calibration is required for optimal accuracy.

5. Conclusion

Techniques allowing small and accurate resonance frequency alteration at fabrication were presented, demonstrated and analyzed. In SiN microrings, a 1-2 GHz frequency control can potentially be attained. In practice, stochastic frequency variations can be sizeable but can be addressed in design with appropriate resonator shape.

6. References

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